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THE EFFECT OF MOISTURE ABSORPTION IN
CLOTHING ON THE HUMAN HEAT BALANCE

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SUMMARY

A theory of moisture absorption in clothing, with the associated ef-
fects of heat transfer, was developed based on the assumption that
clothing can be regarded as a moisture buffering capacitor enclosed
between heat and vapour resistances, and covered with the adjacent air
layer.
The theory was checked with an experiment involving four subjects.
They wore heavy woolen clothing, which was either initially dried or
wetted, in both a warm and a cool environment. The experimental
results confirmed satisfactorily the theoretical predictions that (1)
the dry and evaporative heat loss will change in time and will both
converge for the dry and moist garments to the equilibrium condition,
(2) the clothing surface temperature and humidity are bound to a
straight line on the psychrometric chart, (3) dry garments cause
higher heat strain than wet garments, (4) the time course is pre-
dictable from the buffering capacity of the clothing and the heat
transfer coefficient, and (5) the apparent heat and moisture transfer
coefficients are bound to a linear relationship, revealing the true
values only during equilibrium. Contrary to the expectation the
observed vapour resistance is lower in the heat than in the cold,
probably due to differences in sweat distribution.

Het effect van vochtabsorptie in kleding op de warmtebalans

W.A. Lotens en G. Havenith

SAMENVATTING

Een theorie over vochtabsorptie in kleding en de daarmee gepaard
gaande dynamische warmtetransportverschijnselen werd uitgewerkt,
uitgaande van de veronderstelling dat kleding beschreven kan worden
als een buffercapaciteit tussen damp- en warmteweerstanden en bedekt
met de aanhangende luchtlaag.
De theorie werd getoetst met een experiment waarin vier proefpersonen
dikke wollen kleding droegen die van tevoren was gedroogd of juist
bevochtigd. Dit werd gedaan zowel in een warm als in een koel klimaat.
De resultaten bevestigen de theoretische voorspellingen dat (1) de
droge en natte warmte-afgifte in de tijd veranderen en beide converge-
ren voor droge en vochtige kleding naar de evenwichtstoestand, (2) de
temperatuur en absolute vochtigheid van het kledingoppervlak aan
elkaar gekoppeld zijn en een rechte lijn geven op een psychrometrische
kaart, (3) droge kleding een grotere warmtebelasting geeft dan natte
kleding, (4) het tijdverloop van het absorptieproces voorspeld kan
worden uit de absorptiecapaciteit en de warmte-overdrachtscoëfficiënt
van de kleding, en (5) de schijnbare warmte- en dampoverdrachtscoëffi-
ciënten een lineair verband vertonen en slechts in de evenwichtscondi-
tie hun echte waarde aannemen. In tegenstelling tot de verwachting is
de gemeten dampweerstand in de warmte lager dan in de koele omgeving
wat waarschijnlijk toe te schrijven is aan verschillen in verdeling
van het zweet.

1 INTRODUCTION

The absorption property of fabrics is generally regarded as a prime factor in comfort. There is no clear insight, however, in the contribution to comfort of the many mechanisms involved, including fibre rigidity, wicking, clinging, liquid buffering, drying, and thermal effects. Some of these mechanisms are relevant only during transient conditions. In particular the thermal effects are interesting in this respect, since clothing heat transfer is usually studied in equilibrium conditions, whereas in reality wearers are almost constantly in transient conditions.

Absorption is the link between dry and wet heat transfer in transient conditions. When absorption takes place, the heat of sorption is liberated and consequently the dry heat flow increases, whereas the wet heat flow is decreased. During desorption the opposite occurs. Thus the clothing as worn is continuously buffering and dissipating moisture, with associated heat effects. The quantitative description of this process is the subject of this study.

The importance of the absorption capacity of clothing for actual wear has long been recognized, but hardly been quantified. At the level of fibres the absorption theory had been developed by Cassie and Baxter (1940) and Henry (1939), explaining in particular the surprisingly long time constants involved. Woodcock (1962) recognized the implications for fabrics, but focussed on the vapour resistance. Spencer-Smith (1976, 1978) developed part of the theory involved, but restricted himself to physical measurements, and so did Farnworth (1986), applying a more sophisticated mathematical model.

David (1965) was the first to report the effects of absorption in clothing, using a thermal manikin. He too found longlasting effects.

Recently, De Dear et al. (1989) reported a manikin/subjects study on the thermal effects of moving from one environmental humidity to another with absorbing and non-absorbing clothing. They described part of the effects by a regression model.

The current study is aiming at a simple but realistic theory, predicting quantitatively the thermal effects of absorption on the heat balance of humans.

2 ABSORPTION THEORY

Clothing will be considered as a single layer of uniform properties, covered with the adjacent air layer. The relevant clothing properties

are the heat transfer coefficient, the vapour resistance and the moisture absorption capacity. The latter will be considered to be located in the middle of the clothing layer. Fig. 1 shows this in an electrical network, although the actual analogy to electrical phenomena is poor.
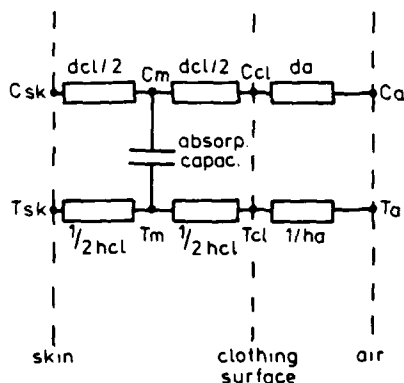
Fig. 1 The considered clothing system in an electrical analogon. The upper chain of resistances (vapour resistance d) and the lower chain of heat resistances (1/h) are connected by the water vapour absorption capacity of the clothing, located in the middle of the clothing layer.

For the description of the theory two locations in the clothing system are relevant. The first is the location of the absorption capacity and the second the interface between clothing and air. The latter place is most apt to experimental check of the theory, whereas the former is decisive for the speed of transient phenomena.

Clothing material has the heat storage capability:

$$\text{Storage} = W\ Cp\ \frac{dTm}{dt}\ (W/m^2) \tag{1}$$

where W = fabric weight (g/m^2)
Cp = specific heat $(J/g°C)$
Tm = temperature in the middle of the clothing $(°C)$.

The magnitude of the heat storage is usually small compared to the amounts of heat that flow from the skin. Only during fast transients,

like step changes in temperature or radiation, the effect is appre-
ciable, but only so for a short time. During a step change of 10°C,
heavy clothing (hcl = 4 W/m²·C, 500 g/m²) will store initially 40 W/m²,
which dies away with a time constant of 120 s, while light clothing
(hcl = 16 W/m²·C, 200 g/m²) stores initially 160 W/m², dying with a
time constant of 12 s. Thus for heavy clothing the heat storage has
decreased to below 10 W/m² within 3 min and for light clothing within
35 s. A flow of 10 W/m² is small compared to the heat production of
humans (50 W/m² in rest, increasing to a multiple during work) and for
the sake of simpleness the heat storage will be neglected in this
study.

The moisture storage capability depends on the sorption capacity of
the fibres, which is characterized by the standard regain (Reg), the
amount of water absorbed at 65% relative humidity (rh) in 100 g of dry
fibre. For all fibres the absorbed water (Ma) is approximately in the
same way dependent on the relative humidity (rh), following a typical
absorption function f. Thus fabrics of various fibre types differ only
in the proportionality factor Reg:

$$Ma = \frac{Reg}{100} \; f(rh) \quad (g \; H_2O/g \; fibre) \tag{2}$$

and a change in Ma is defined by

$$dMa = \frac{Reg}{100} \; f' \; drh \quad (g/g) \tag{3}$$

where f' = derivative of f with respect to rh.

This change in moisture content of the fibre is associated with the
liberation or absorption of the differential heat of sorption Qv,
which is also a typical function of the relative humidity. The heat
involved is thus:

$$Abs = W \; Qv \; \frac{dMa}{dt} = \frac{W \; Qv \; Reg}{100} \; f' \; \frac{d \; rh}{dt} \quad (W/m^2) \tag{4}$$

where W = weight of fabric (g/m^2).

Abs is the power involved in the transition from an evaporative into a
dry heat flow (during absorption) or the other way around (during
desorption). The sum of dry and evaporative heat flows is for any
place in the ensemble not affected by this transition:

$$Dry + Evap = Constant$$

Since it was assumed that the heat storage in the clothing can be neglected, the total heat flow from the skin to the clothing must equal the flow from the clothing to the environment:

$$Dry_{sc} + Evap_{sc} = Dry_{ca} + Evap_{ca} \qquad (5)$$

where sc refers to skin → clothing
       ca refers to clothing → air.

Similar equations hold for any place inside the clothing system. With reference to the clothing surface the four terms in equation 5 are defined by:

$$Dry_{sc} = hcl \ (Tsk - Tcl) \qquad (6)$$

$$Evap_{sc} = Qv \ \frac{D}{dcl} \ (Csk - Ccl) \qquad (7)$$

$$Dry_{ca} = ha \ (Tcl - Ta) \qquad (6a)$$

$$Evap_{ca} = Qv \ \frac{D}{da} \ (Ccl - Ca) \qquad (7a)$$

where h = heat transfer coefficient $(W/m^2 °C)$
       D = diffusion coefficient (m^2/s)
       d = diffusion air equivalent (m)
       T = temperature (°C)
       C = water vapour concentration (g/m^3)
       sk refers to skin, cl to clothing, and a to air.

Substitution of 6, 6a, 7 and 7a into 5 reveals:

$$Tcl(ha+hcl) + Ccl \ Qv \ D \ (\frac{1}{da} + \frac{1}{dcl}) =$$
$$= hcl \ Tsk + ha \ Ta + Qv \ D \ (\frac{Csk}{dcl} + \frac{Ca}{da}) \qquad (8)$$

Equation 8 represents a linear relationship between Tcl and Ccl for any set of skin and environmental conditions. In Fig. 2 the relationship is plotted in a psychrometric chart.
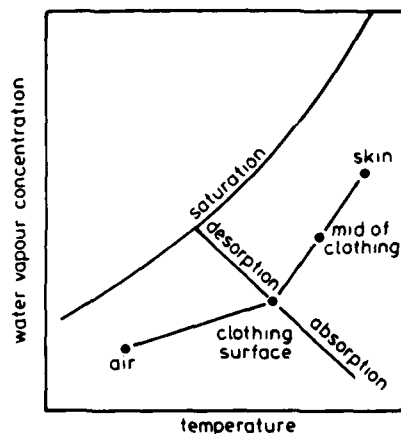
Fig. 2 Psychrometric chart, showing the condition at the skin and in the air. The straight line is the locus of solutions of equation 8 for the temperature and vapour concentration at the clothing surface. The condition of the mid of the clothing is always halfway the skin and the surface condition.

Any point at the line represents a solution for equation 8. The difference between the solutions is the rate of absorption or desorption. During absorption the clothing is relatively dry, Ccl is low and due to liberation of heat of sorption Tcl is high. This is the case in the bottom part of the line. During desorption Ccl is high and Tcl is low, a condition represented by the top part of the line. In between these two, there is a point of equilibrium, for which holds:

$$Dry_{sc} - Dry_{ca}$$

$$Evap_{sc} - Evap_{ca}$$

The condition of the clothing thus tends to converge to the equilibrium point, starting from the extremities. So far the theory is essentially the same as presented by Spencer-Smith (1978).
The speed of convergence depends on the sorption process, which is defined by:

$$Abs - Evap_{sc} - Evap_{ca} \tag{9}$$

As was anticipated, for the calculation of transients $Evap_{sc}$ and $Evap_{ca}$ should be defined with reference to the midpoint of the clothing, rather than to the surface:

$$Evap_{sc} = 2 \; Qv \; \frac{D}{dcl} \; (Csk - Cm) \tag{7b}$$

$$Evap_{ca} = 2 \; Qv \; \frac{D}{dcl + 2 \; da} \; (Cm - Ca) \tag{7c}$$

Similarly Dry_{sc} and Dry_{ca} read:

$$Dry_{sc} = 2 \; hcl \; (Tsk - Tm) \tag{6b}$$

$$Dry_{ca} = \frac{2 \; ha \; hcl}{2 \; hcl + ha} \; (Tm - Ta) \tag{6c}$$

Similar to equation 8 a relationship between Cm and Tm can be found:

$$
\begin{aligned}
Tm \; (\frac{2 \; ha \; hcl}{2 \; hcl + ha} + 2 \; hcl) + Cm \; Qv \; D \; (\frac{2}{dcl} + \frac{2}{dcl + 2 \; da}) = \\
= 2 \; hcl \; Tsk + \frac{2 \; ha \; hcl}{2 \; hcl + ha} \; Ta + Qv \; D \; (\frac{2 \; Csk}{dcl} + \frac{2 \; Ca}{dcl + 2 \; da})
\end{aligned}
\tag{8a}
$$

When the midpoint of the clothing changes in relative humidity by d rh, equation 4 can be written as:

$$
\begin{aligned}
Abs = \frac{W \; Qv \; Reg \; f'}{100} \; \frac{dCm/Csat}{dt} = \\
= \frac{W \; Qv \; Reg \; f'}{100 . Csat} \; (\frac{dCm}{dt} - \frac{Cm}{Csat} \; C' \; \frac{dTm}{dt})
\end{aligned}
\tag{4a}
$$

where Csat = saturation concentration at temperature Tm (g/m^3)

C' = dCsat/dTm ($g/m^3 \cdot °C$).

From equation 8a it follows that (at stationary boundary conditions):

$$\frac{dTm}{dt} = - \frac{Qv \; D \; (\frac{2}{dcl} + \frac{2}{dcl + 2 \; da})}{\frac{2 \; ha \; hcl}{2 \; hcl + ha} + 2 \; hcl} \; \frac{dCm}{dt} \tag{10}$$

When equations 7b and 7c are substituted in 9, and 9 and 10 are substituted in equation 4a, a non-linear differential equation is obtained:

$$\frac{dCm}{dt} = \frac{Cm - Ce}{\frac{W\,Reg\,f'}{100.4.Csat}\left(\frac{dcl\,(dcl+2\,da)}{D\,(dcl+da)} + \frac{Cm}{Csat}\,C'\,\frac{Qv}{hcl}\,\frac{(2\,hcl+ha)}{(hcl+ha)}\right)} \quad (s)(11)$$

where Ce = equilibrium value for Cm.

Equation 11 can be considered as a linear first-order differential equation with a continually changing time constant equal to the de-nominator of 11. This time constant is long for:large absorption capacity (W.Reg), high relative humidity (f' and Cm/Csat), low tem-perature (low Csat), thick clothing (high dcl and low hcl), and still air (low ha and high da). The change of the time constant during the process is not so large, becoming shorter during desorption and longer during absorption.

For a .6 clo cotton garment of 300 g/m^2, equation 12 predicts during comfortable conditions a time constant of about 2 minutes, when equi-librium is near. This is only an approximate value, since in reality the surface of the clothing has a shorter time constant than the innermost layers. In order to keep the theory simple such a distinc-tion in time constants will not be made in this study.

A quantitative predictive model should allow the calculation of the transient effects. Such a model has been implemented on a computer (Program MDC, Moisture Dynamics of Clothing) to obtain numerical results. For the clothing specified in Table I, the results are given in Fig. 3.

Table I **Specification of the clothing and boundary con-ditions in the calculation of Fig. 3.**

Garment		Skin		Environment	
hcl	= 8 W/m^2°C	Tsk	= 35°C	Ta	= 15°C
dcl	= 11 mm	Csk	= 25 g/m^3	Ca	= 8 g/m^3
W.Reg/100	= 50 g/m^2			da	= 4 mm
				ha	= 12 W/m^2°C

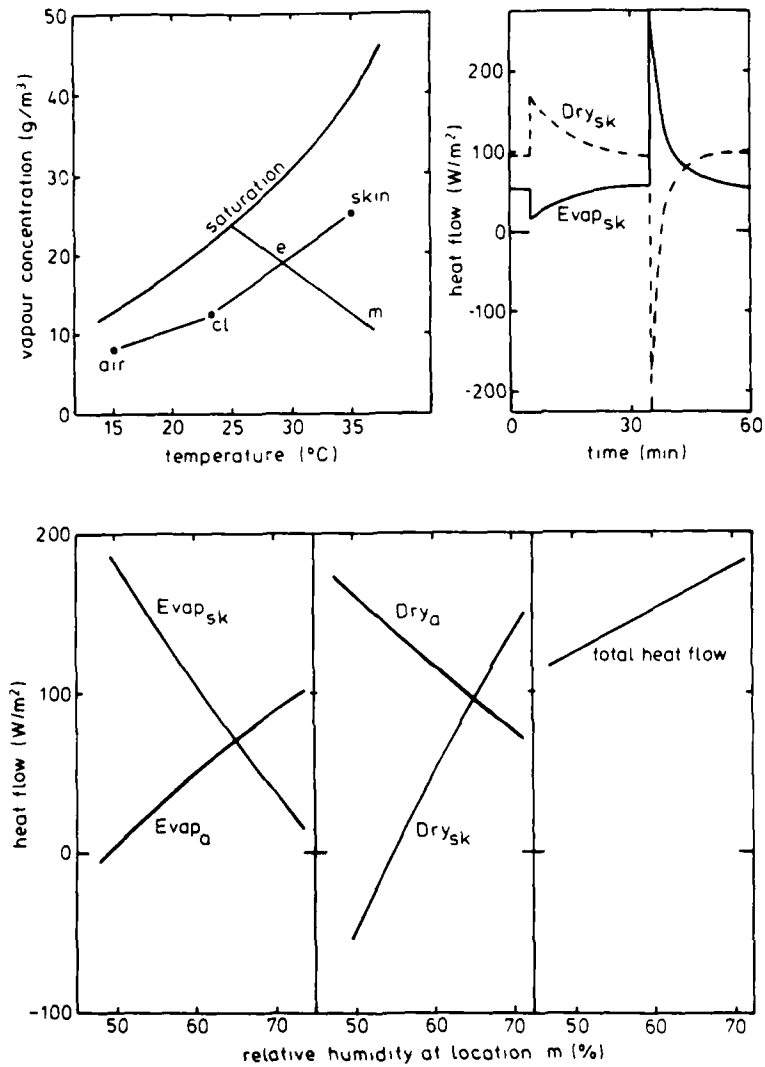Fig. 3 Results of a numerical analysis of transients in the clothing specified in Table I. Top left panel: psychrometric chart with the locus of solutions for the middle of the clothing (m). Top right panel: skin heat flow components following wetting of the clothing (min 5) and drying (min 35). Bottom panel: heat flows at the skin and to the air, and total heat flow as a function of clothing relative humidity.

The top-left panel shows the skin, air and clothing surface conditions in a psychrometric chart. The line is the locus of solutions of equation 8. In the top-right panel, the responses are shown of the dry and evaporative heat flow to full saturation of the clothing (100% rh, min 5) and fully drying the clothing (0% rh, min 40). In particular for dry clothing the rate of absorption is so high that the clothing temperature increases to over 35°C, resulting in a negative dry heat flow between skin and clothing. For the parameters chosen, the response time is of the order of 8 min. The bottom panel of Fig. 3 shows the resultant heat flows to and from the clothing as a function of the relative humidity of the clothing. At 65% there would be equilibrium. Depending on the relative humidity, the various heat flows may change dramatically and in particular the differences between the heat flows to and from the clothing may be large. In the same graph, finally, the total heat flow is shown that leaves the skin. This flow increases with the relative humidity of the clothing, indicating that moist clothing is less stressful than dry clothing.

The heat flows in Fig. 3 at the skin and into the air are not the same as those of equations 7b and 7c. In those equations the clothing condition as to C_{cl} is defined on the basis of Q_v, the heat of sorption. At the skin there is liquid that evaporates and there the heat of evaporation H_e is pertinent. The evaporative heat flows from the skin and into the environment thus read:

$$\text{Evap}_{sk} = \frac{2 \ H_e \ \mathbb{D}}{d_{cl}} \ (C_{sk} - C_m) \tag{7d}$$

$$\text{Evap}_{a} = \frac{2 \ H_e \ \mathbb{D}}{d_{cl} + 2 \ d_a} \ (C_m - C_a) \tag{7e}$$

where the subscripts sk and a refer to skin and air, and should be distinguished from the earlier introduced subscripts sc and ca, which referred to the heat balance in the clothing. For reasons of symmetry also Dry_a and Dry_{sk} are introduced, but these equal Dry_{ca} and Dry_{sc}, respectively.

In experiments only the heat loss of subject plus clothing is really accessible for measurement. This is $\text{Dry}_a + \text{Evap}_a$. These equal $\text{Dry}_{sc} + \text{Evap}_{sc}$, defined by 6b and 7d:

$$\text{Dry}_a + \text{Evap}_a = 2 \ h_{cl} \ (T_{sk} - T_m) + \frac{2 \ H_e \ \mathbb{D}}{d_{cl}} (C_{sk} - C_m) \tag{12}$$

Since T_m and C_m are not readily available this equation must be converted to terms in T_{cl} and C_{cl}, recognizing that:

$$Tm = Tcl + \frac{Dry_a}{2 \ hcl} \tag{13}$$

$$Cm = Ccl + \frac{dcl \ Evap_a}{2 \ He \ D} \tag{14}$$

Substitution of 13 and 14 in 12 reveals that

$$Dry_a + Evap_a = hcl \ (Tsk\text{-}Tcl) + \frac{He \ D}{dcl} \ (Csk - Ccl) \tag{12a}$$

In this equation all variables except hcl and dcl are measurable and equation 12a is thus one equation with two unknown variables. The solutions are multiple and form a straight line when hcl is plotted against 1/dcl. Only during real equilibrium the actual clothing parameters are found:

$$hcl = \frac{Dry_a}{Tsk\text{-}Tcl} \tag{15}$$

$$dcl = \frac{He \ D \ (Csk\text{-}Ccl)}{Evap_a} \tag{16}$$

When equations 15 and 16 are applied before equilibrium is settled, the apparent clothing parameters are obtained.

The sorption theory thus leads to a number of important notices that are suited for experimental verification:

I   dry and moist garments show rather different Dry_a (and $Evap_a$), converging to the same equilibrium value;

II   the same is true for Tcl and Ccl, which are bound to the straight line in Fig. 2;

III   the body heat loss is lower for a dry than for a moist garment, resulting in a higher heat strain;

IV   the time course is predicted by equation 11;

V   when applying a heat balance technique to obtain hcl and dcl, the apparent values change with the time and the real values are obtained only when equilibrium is reached. The apparent hcl and 1/dcl lay on a straight line.

3   EXPERIMENTAL VERIFICATION

3.1   Methods

The theory was tested in an experiment where subjects performed work
on a bicycle ergometer, clothed in absorbing clothing. The outer
garment was either initially dried or wetted to approximately 90% rh
According to equation 12a, the apparent values of hcl and 1/dcl found
during the absorption or desorption phase should lay on a straight
line, and the equilibrium, that is not likely to be reached within an
acceptable experimental trial, is somewhere in between. To find the
equilibrium point, a second line, crossing the first, would be help-
ful. This can be obtained by repeating the measurements in other
environmental conditions, as equation 13a again predicts. In the
experiment a cool (9.5°C, 52% rh) and a warm (26.8°C, 24% rh) condi-
tion were chosen, with predominantly dry and evaporative heat trans-
fer, respectively. For these four conditions (moist/dry combined with
warm/cool) the heat balance equation was determined at three consecu-
tive times to show the process of convergence of the moist and dry
conditions with time.
Details about the experimental set-up are given below.
- Clothing. Cotton fatigues (1300 g) under a woolen fire-fighters
  garment (1700 g for the jacket and 900 g for the trousers). The
  fabric's outer surface area is 2.2 m². Completed with rubber boots,
  rubber gloves, respirator and impermeable hood, together .5 m² area.
- Clothing wetness. Dry fatigues and either tumbler-dried woolen
  garment, or tumbler-dried and then wetted with 400 g water in the
  jacket and 300 g in the trousers, giving relative humidities of
  around 10 and 90%, respectively.
- Subjects. 5 males in the age of 21 to 25 years, with a DuBois sur-
  face area between 1.7 and 2.1 m² (average 1.9 of which 1.6 m² is
  covered with clothing and .3 m² with impermeables), training level
  varying from bad to very good. One subject completed only 2 condi-
  tions due to illness.
- Environment. Either 26.8°C, 24% or 9.5°C, 52%, resulting water
  vapour concentrations of 6 and 4.8 g/m³, respectively. Horizontal,
  slightly turbulent air flow of average speed .25 m/s.
- Work. Bicycle ergometer work of 70 W external work (Wext), resulting
  in 442 W metabolic work (M) on the average. Due to a malfunction of
  the bicycle feedback control system and individual variation the
  metabolic energy production has not been the same for all condi-
  tions, but varied from 380 to 480 W.

- **Sessions**. Duration 1 hour. Heat balance has been determined at min 30, 45 and 60. Preparation of the subjects took place in a room at 23°C. The subjects entered the climatic chamber immediately upon donning the conditioned woolen garment.
- **Measurements**. O2 uptake, CO2 production, heart rate, rectal temperature, skin temperature at seven sites (head, chest, back, upper arm, lower arm, thigh, calf), skin vapour concentration at the same sites, clothing surface temperature at the same sites, continuous weight registration, perceived temperature and wetness, weight of garments before and after test.
- **Data reduction**. Heat balance data (Evap$_a$ and heat storage, Sto), were transformed to M - 442 W by means of regression analysis (r - .95 for Evap, .8 for Sto). Respiratory heat loss and dry heat loss from impermeable parts are calculated by:

$$Resp = .0024\ M\ (42 - Ca) + .0014\ M\ (34 - Ta)$$

$$Dry' = 1.93\ \Delta T$$

where 1.93 = heat conduction from head, hands and feet, calculated from the insulation thickness and the area (W/°C)

ΔT = temperature difference between the average of head, lower arms and calves, and air.

3.2   Results

Prediction I (wet and dry conditions show converging heat balance)
The heat balance has the form

$$M = Wext + Resp + Dry' + Dry_a + Evap_a + Sto$$

where Dry' is the heat loss of head, hands and feet. The heat balance amounts then in the cold to

$$442 = 70 + 57 + 46 + Dry_a + Evap_a + Sto$$

and in the heat to

$$442 = 70 + 46 + 13 + Dry_a + Evap_a + Sto$$

The average values of Dry$_a$, Evap$_a$ and Sto are shown in Fig. 4. In concert with prediction I of the theory there is convergence in time of the wet and dry conditions.
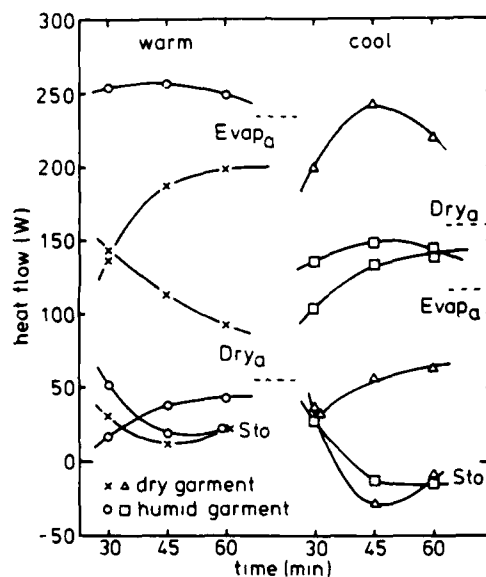
Fig. 4   Experimentally determined heat flows as a func-
tion of time for the cool and the warm environment, both
starting with a dry and a humid garment.

The difference in environmental condition between the preparation room and the climatic chamber causes a strong initial transient, enhanced by the transient in skin condition (Fig. 8) associated with the onset of work. After about 30 min these boundary conditions become more stable and from that time on Evap a, Dry a and Sto show the expected behaviour. Although the equilibrium comes nearer in the second half hour, it is by far not reached at min 60.

Prediction II (Tcl and Ccl are on a straight line)
That after 60 min there is still no equilibrium, is confirmed by the surface temperatures of the clothing, shown in Fig. 5.
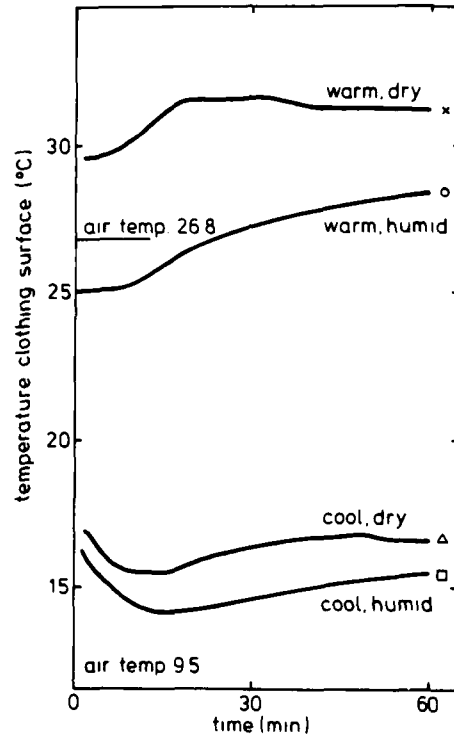
Fig. 5 Clothing surface temperature as a function of
time for the cool and the warm environment, both with a
dry and a humid garment.

The dry conditions both show higher temperatures than the correspond-
ing humid conditions, due to the liberation of heat in the dry condi-
tion and the absorption in the humid case. The curves are pairwise
slowly converging as predicted. The difference between Tcl and Ta is
largest in the cool, dry condition and smallest in the warm, humid
condition. In Fig. 6 these gradients are plotted against Dry$_a$ for the
four conditions and for min 30, 45 and 60.
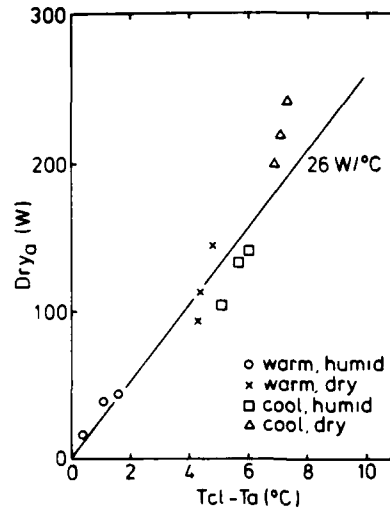
Fig. 6 Correlation between the dry heat flow to the air and the temperature gradient between garment surface and air. The three data points for each condition pertain to the minutes 30, 45 and 60.

There is a proportionality, revealing a heat transfer coefficient of 26 W/°C, which corresponds to 11.8 W/m²°C. With a radiative heat transfer coefficient of 4.5 (assuming an emission coefficient of 1 and an effective radiating surface area of 90% of the clothing area), this leaves for the convective part of ha (hc) a value of 7.3. The values of Ccl may now be calculated according to

$$Ccl = Ca + \frac{Evap_a}{Acl} \frac{da}{He \ D} = Ca + \frac{Evap_a}{Acl \ hc \ L} \quad (g/m^3) \quad (17)$$

where Acl = the clothing surface area (2.2 m²)

L = Lewis constant (2.34°Cm³/g).

The values of Ccl thus found are plotted against Tcl in Fig. 7 and also the predicted values are indicated, applying equation 8.
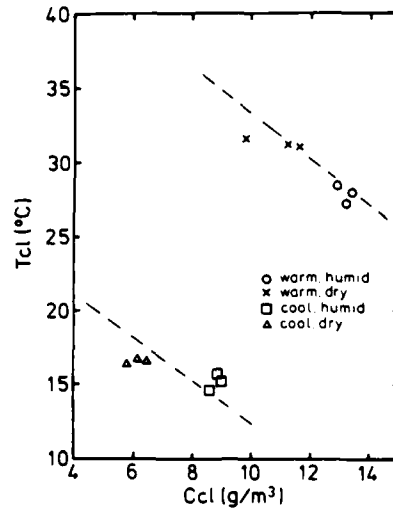
Fig. 7 The data points and the predicted relationship between the clothing surface temperature and vapour concentration in their approach to equilibrium. The three data points per condition pertain to minutes 30, 45 and 60.

For the calculation of the theoretical lines the actual Tsk and Csk are used, as well as the resultant hcl and dcl which will be dealt with later. The fact that the data points in Fig. 7 are not exactly on a straight line is largely due to non-stationarity of the skin temperature and vapour concentration.

Prediction III (dry clothing produces higher heat strain)
The effect of environmental temperature and clothing humidity is reflected in the skin temperature and vapour concentration. Fig. 8a shows that the skin temperature is higher for dry than for humid clothing and the same holds for the vapour concentration, except for the cool condition at min 60. The difference in vapour concentration is not large enough, however, to become statistically significant.
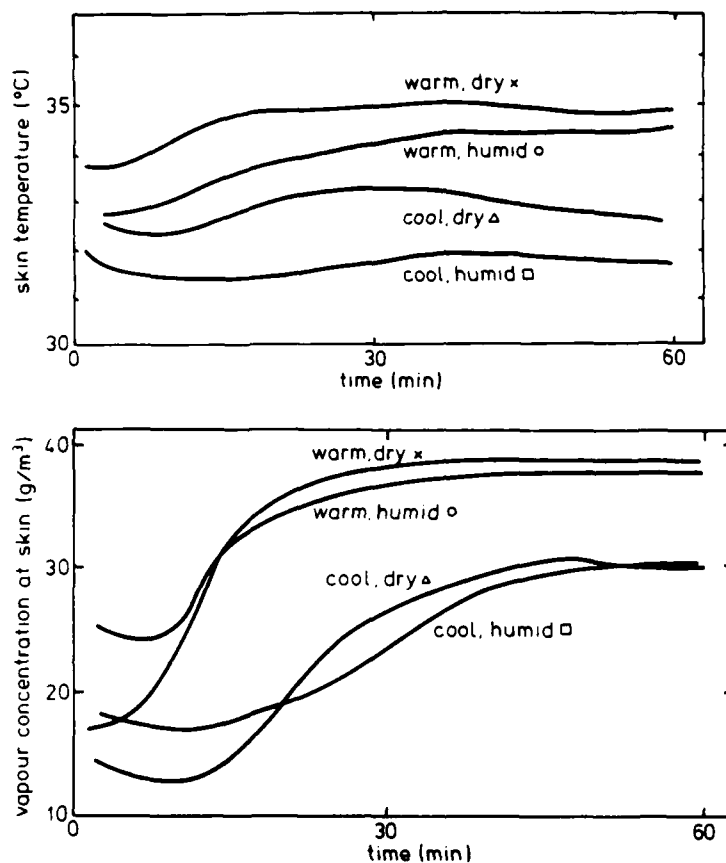
Fig. 8 Skin temperature (a) and skin vapour concentration (b) as a function of time.

There are more indications of higher heat strain in dry clothing, which are collected in Table II. Of the included variables only Tsk and sweat production are statistical significantly different between dry and humid clothing, but all variables indicate the same trend. During transient condition skin temperature is higher in dry clothing, rectal temperature is marginally higher, heart rate is higher (probably due to skin temperature), the skin relative humidity is slightly lower, and the sweat production is considerably higher.

Table II   Indicators of heat strain at min 60. Tsk is
skin temperature, Tr is rectal temperature, HR is heart
rate, RHsk is skin relative humidity, SP is sweat pro-
duction.

Condition	Tsk (°C)	Tr (°C)	HR (min^{-1})	RHsk (%)	SP (g/h)	heat rating	wetness rating
warm, dry	34.9	37.8	129	98	506	very warm	wet everywhere
warm, humid	34.5	37.7	124	98	161	warm	wet everywhere
cool, dry	32.6	37.7	114	86	206	slightly warm	locally wet
cool, humid	31.6	37.6	111	90	30	slightly warm	locally wet

The subjective heat and wetness ratings are different between the warm
conditions only. It should be noted that the number of subjects is too
low to expect any significant difference in subjective ratings.

Prediction IV (time course predicted by equation 11)
The final values of Tsk and Csk, and the estimated real values of hcl
and dcl have been used to predict the time course of Dry$_a$ by means of
the computer program MDC. This is thus a simulation with constant
boundary conditions, in contrast to the experiment in which during the
first halfhour (warm environment) or three quarters of an hour (cool
envir.) the skin condition was changing. In Fig. 9 the result of the
simulation is shown together with the measured values for Dry$_a$.
In the warm conditions the prediction is close to the measurement, but
in the cool condition there is some deviation due to the continuing
change in skin humidity until min 45. Both in the warm and in the cool
conditions the predicted convergence seems somewhat slower than the
measured convergence. It is hard to estimate the actual time constants
from the half hour period available, but the time constant for conver-
gence is of the order of 30 min in the warm and 50 min in the cool
condition.
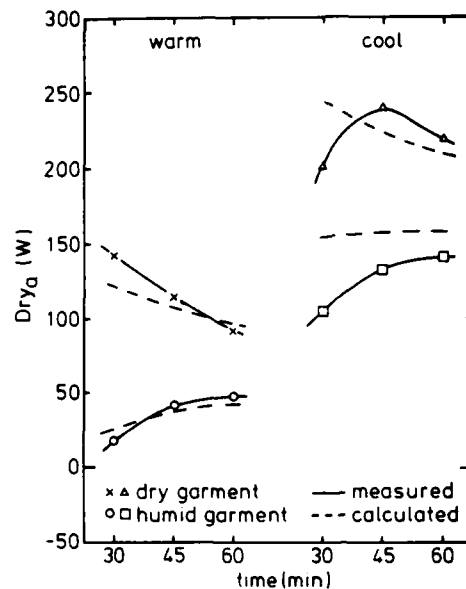
Fig. 9 The measured (solid lines, same as Fig. 4) and the predicted (interrupted lines) dry heat loss to the environment as a function of time.

Also the moisture content of the clothing and the sweat evaporation after min 60 contains some information on the time course, but this information is an integration over the full experimental session and is not simple to deduct theoretically, due to the dry conditioning of the fatigues in all sessions and the changes in skin condition in the first period of the session. Table III shows the moisture cumulation data.

Table III Moisture cumulation over 60 min (in g).

Condition	Sweat prod.	Fatigues	Outer garment	Evaporated
warm, humid	161	175	-352	338
warm, dry	506	198	115	193
cool, humid	30	60	-225	195
cool, dry	206	35	112	59

The difference in moisture content of the outer garment between the humid and the dry condition is 233 g in the warm and 363 g in the cool condition. This is a qualitative support for the predicted shorter time constants in warm conditions according to equation 12. This is no more than an indication since it will be shown in the next section that dcl, which also has effect on the time constants, is not equal for the warm and the cool conditions.

Prediction V (hcl and 1/dcl are on a straight line)

When equations 16 and 17 are applied to the non-equilibrium situation, the apparent values of hcl and dcl are found. Only during equilibrium these equal the real values. Equation 13a predicts that there is a linear relationship between the apparent values of hcl and 1/dcl. The predicted relationships have been calculated for the four conditions. Fig. 10 shows that in the heat there is good agreement with the prediction and in the cold also, with the exception of one point in the cool, dry condition.
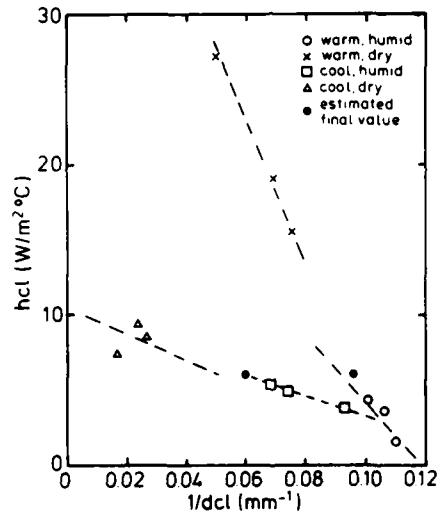
Fig. 10 The apparent values of hcl and 1/dcl in their approach to the equilibrium and the estimated final values (dots). The dashed lines represent the theoretical prediction. The three data points for each condition pertain to min 30, 45 and 60.

The equilibrium condition should theoretically be at the crossing of the two lines and that was the reason to have warm and cool conditions. Here is a considerable deviation of the expectations, however.

The actual crossing is definitely outside the area where equilibrium is expected. Probable equilibrium values are estimated from extrapolations of $Evap_a$, Dry_a, Tsk-Tcl and Csk-Ccl and amount to hcl = 6.0 $W/m^2°C$ for both the warm and cool condition, and dcl = 16 mm in the cool condition, in contrast to 10.4 mm in the warm condition. The consistency of all data suggests that this is a true effect. One cause could be that the fatigues were much wetter in the warm conditions (water uptake ≈ 185 g) than in the dry conditions (≈ 50 g), enabling liquid transport in addition to vapour transport, and another cause could be that in the heat the sweat production is for a larger proportion taking place at the legs, where the vapour resistance is lower than on the trunk, due to less insulation and more motion.

3.3   Discussion

The estimated final values for hcl (6 $W/m^2°C$ both in the heat and in the cold) and dcl (10.4 mm in the heat and 16 mm in the cold) are credible values for the type of clothing used. According to Lotens and Havenith (19..) cycling will decrease the insulation by some 25% for the cycling frequency used (50 rpm) and thus the estimated hcl for standing persons would be about 4.5. This is the heat transfer coefficient for a body that is half covered with 3 layers and for the other half with 2 layers of clothing. The local heat transfer coefficients would be

	standing			cycling	
	hcl	radiative part	convective part	hcl	convective part
3 layers	3.6	5/3	1.9	4.8	3.1
2 layers	5.4	5/2	2.9	7.2	4.7

The radiative part of hcl has been estimated here as

$$hclr = \frac{5}{\# \text{ intermittent layers} + 1} = \frac{5}{\text{total } \# \text{ layers}} \qquad (18)$$

as simple physics predict (Lotens, 1989).

Since the vapour resistance can be estimated as

$$d = 1.3 \frac{\lambda a}{hclc} + .001 * \# \text{ layers (m)} \tag{19}$$

where λa = heat conductivity of air (.026 W/m^2°C)

hclc = convective part of hcl

(Lotens and Havenith, 19..), the corresponding vapour resistances would be

	dcl (standing)	dcl (cycling)
3 layers	21 mm	14 mm
2 layers	14 mm	9 mm

The values thus found seem to agree reasonably well with the experiment. When it is mainly the trunk that sweats, the 3-layer (standing) condition is the most relevant (since the upper body moves not so much during cycling) whereas additional sweating on the moving legs may decrease the dcl value to somewhere in between 21 and 9 mm. The hypothesis that the difference in dcl between the warm and the cool condition is due to a shift in sweat distribution thus seems to be supported.

Another aspect of the sweat mechanism is the large difference in sweat production between the humid and dry condition. Table III showed that the sweat production was 345 g/h larger with a dry garment in the heat and 176 g/h in the cold. The concomitant differencᵉᵉ in Tsk (1°C in the cold, .4°C in the heat) and in Tr (.1°C bᵒth in the cold and the heat) are insufficient to explain the difference in sweat production. According to Nadel et al. (1971) sweat production is largely controlled by core, mean skin and local temperature, and to a smaller magnitude by the rate of change in Tsk. These factors woːld explain only 45 g/h in the heat and 70 g/h in the cold in the current situation. Apparently the vapour concentration gradient has an enhancing effect on the sweat production. Although this has been reported earlier (Nadel and Stolwijk, 1973) the magnitude seems larger in this study. A cause could be the inhibitory effect of saturated skin on sweat production, known as hydromeiosis (Brown and Sargent, 1965).

The predictive formula for the time course (equation 1) looks rather complicated but some of the terms involved are more or less constant for not too extreme circumstances. Using the relationships 18 and 19 to convert dcl into hcl, the time constant in 11 can be simplified to

$$\tau = \frac{W \text{ Reg}}{100} \cdot \frac{60}{hcl} \text{ (s)} \tag{12a}$$

This is an approximate value, where W Reg/100 is the absorption capacity (defined as g H20 absorbed at 65% rh per m^2 of fabric).

For the garment in this experiment r is 309 * 60/6 = 3090 s ≈ 52 min. The transient will typically last for $3r$. This means that for the current highly absorbing clothing an experimental session should have lasted for about 3 h to arrive at the final values for hcl and dcl. With more usual clothing (h = 8, absorption capacity 50 g/m^2) the r time would be over 6 min and consequently the transient is extinguished about 20 min after the skin condition has stabilized. Such a time course was indeed measured by David (1965) when moving a clothed manikin from a dry into a humid environment. Determining the heat balance at an earlier moment than after $3r$ with the intention to establish hcl and dcl would reveal wrong values.

De Dear et al. (1989) found for a 1 clo woolen ensemble of 96 g/m^2 absorption capacity a time constant shifting from 17 to 83 min while measuring heat loss with a manikin. The above rough estimate (12a) would amount to 15 min. Running the program MDC for their data provides time constants decreasing from 40 to 12 min when moving to the dry environment, and increasing from 10 to 20 min when moving to the humid environment. The apparent discrepancy with the manikin data might well be due to the earlier mentioned larger time constants for the inner clothing layers.

Although the model predicts heat flows and is not designed for comfort evaluation, some qualitative statements on comfort can be justified. It was predicted and confirmed that in the absorbing phase the total heat flow is lower than in the desorbing phase and the heat stress consequently larger. When approaching the equilibrium the difference becomes small. What would be the immediate effect of a change in conditions on the evaporative and the dry part of the heat flow separately? According to the theory the sum of the two is constant for small excursions and they are consequently complementary. It depends on the exact change in the boundary conditions how the heat flows react, but showing one is enough. This is done in Fig. 11 for four ways to induce a step change in condition: by Ta, Ca, Tsk and Csk, using the predictive model.

It is shown (for the conditions specified in Table II) that a step change in environmental condition evokes a smaller than proportional initial jump in the relevant skin heat flow, followed by a gradual change until the new equilibrium is reached. A step change in skin condition, in contrast, evokes a more than proportional initial jump, followed by a reversed transient. It is thus predicted that shocks in environmental temperature or humidity are damped by absorbing clothing, while there is an immediate response to a cooling requirement

from the skin. This could in part explain the common experience that during strenuous work in a varying environment absorbing clothing is more comfortable than non-absorbing clothing.

Cassie (1962) measured the heat loss from a "sweating" manikin and indeed found peaks in heat loss very similar to that of the bottom panel of Fig. 11, with the difference, however, that he was wetting the fabric with liquid, instead of with vapour so that the peak becomes visible in the total of Dry_{sk} and $Evap_{sk}$ as well.
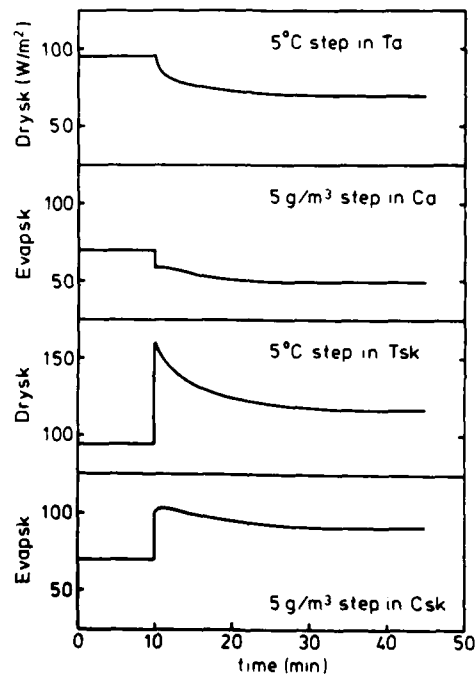
Fig. 11 The predicted response of Dry_{sk} following a step in Ta (top panel) and Tsk (third panel), and of $Evap_{sk}$ following a step in Ca (second panel) and Csk (bottom panel) for the conditions specified in Table II.

De Dear et al. (1989) measured skin temperature and comfort votes of subjects wearing woolen and polyester garments, during up and down steps of the environmental relative humidity. Our model predicts that during an up-step the dry heat flow from the skin shows a dip which fades away with a time constant dependent on the absorption capacity

of the clothing. This would be reflected in a peak in skin tempera-
ture. That is exactly what De Dear et al. found. Skin temperature (2
subjects only) rose some few tenth of a degree C, falling again to a
new level, resulting from the redistribution of metabolic heat over
evaporative and dry heat loss. The associated thermal sensation is
somewhat different: the peak following an up-step in environmental
humidity is rather obscure, whereas the dip following a down-step is
enhanced. De Dear et al. ascribe this to a difference in sensitivity
for skin heating and skin cooling.

4   CONCLUSIONS

- The quantitative theory, describing the rate of dry and evaporative
  heat transfer in clothing during transient conditions, provides a
  satisfactory description of the observed heat flows and tempera-
  tures, despite the fact that the theory assumes clothing to be a
  single homogeneous layer, covered with a surface air layer. The
  characteristics of the clothing are defined in terms of heat trans-
  fer coefficient (hcl), water vapour resistance (dcl) and moisture
  absorption capacity.
- During transients in absorbing clothing the dry and evaporative heat
  flows from skin to clothing are different from those to the environ-
  ment. In classical indirect calorimetry the latter are measured.
  Moreover, the values change in time. The sum of the dry and evapora-
  tive heat flow is the same inside and outside the clothing.
- Absorbing clothing tends to moderate the effect of a change in
  environmental condition on the heat flows at the skin, but enhances
  the effect of a change in skin condition.
- During desorption (thus with moist clothing) there is more heat
  stress than during absorption (with dry clothing).
- During transients the surface temperature and vapour concentration
  of the clothing change, following a linear relationship: when the
  temperature increases, the vapour concentration decreases, and the
  other way around.
- The time constant of this process is approximately 60/hcl seconds
  per gram of moisture absorption capacity of the clothing.
- Since the heat flows observed in indirect calorimetry change in
  time, the accordingly calculated hcl and dcl change as well. The
  experiment should last three times the time constant to reveal the
  equilibrium (true) value. Before that moment the apparent values are

obtained. The apparent hcl is linearly related to the inverse of the apparent dcl.

- When different environmental conditions are applied in a test with subsequent differences in heat strain, it should be recognized that uneven clothing distribution over the body may cause real differences in dcl due to differences in sweat distribution.

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The effect of moisture absorption in clothing on the human heat balance

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15. ABSTRACT (MAXIMUM 200 WORDS, 1044 BYTE)

A theory of moisture absorption in clothing, with the associated effects of heat transfer, was developed based on the assumption that clothing can be regarded as a moisture buffering capacitor enclosed between heat and vapour resistances, and covered with the adjacent air layer.
The theory was checked with an experiment involving four subjects. They wore heavy woolen clothing, which was either initially dried or wetted, in both a warm and a cool environment. The experimental results confirmed satisfactorily the theoretical predictions that (1) the dry and evaporative heat loss will change in time and will both converge for the dry and moist garments to the equilibrium condition, (2) the clothing surface temperature and humidity are bound to a straight line on the psychrometric chart, (3) dry garments cause higher heat strain than wet garments, (4) the time course is predictable from the buffering capacity of the clothing and the heat transfer coefficient, and (5) the apparent heat and moisture transfer coefficients are bound to a linear relationship, revealing the true values only during equilibrium. Contrary to the expectation the observed vapour resistance is lower in the heat than in the cold, probably due to differences in sweat distribution.

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